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3 **The environmental footprint of a membrane bioreactor treatment process through**
4 **Life Cycle Analysis**

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14 **Abstract**

15 This study includes an environmental analysis of a membrane bioreactor (MBR), the
16 objective being to quantitatively define the inventory of the resources consumed and
17 estimate the emissions produced during its construction and operation. The environmental
18 analysis was done by the life cycle assessment (LCA) methodology, in order to establish
19 with a broad perspective and in a rigorous and objective way, the environmental footprint
20 and the main environmental hotspots of the examined technology. Raw materials,
21 equipment, transportation, energy use, as well as air- and waterborne emissions were
22 quantified using as a functional unit, 1 m³ of urban wastewater. SimaPro 8.0.3.14 has been
23 used as the LCA analysis tool, and two impact assessment methods, i.e. IPCC 2013 version
24 1.00 and ReCiPe version 1.10, have been employed. The main environmental hotspots of
25 the MBR pilot unit were identified to be the following: (i) the energy demand, which is by
26 far the most crucial parameter that affects the sustainability of the whole process, and (ii)
27 the material of the membrane units. Overall, the MBR technology was found to be a

28 sustainable solution for urban wastewater treatment, with the construction phase having a
29 minimal environmental impact, compared to the operational phase. Moreover, several
30 alternative scenarios and areas of potential improvement, such as the diversification of the
31 electricity mix and the material of the membrane units, were examined, in order to
32 minimize as much as possible the overall environmental footprint of this MBR system. It
33 was shown that the energy mix can significantly affect the overall sustainability of the
34 MBR pilot unit (i.e. up to 95% reduction of the total greenhouse gas emissions was
35 achieved with the use of an environmentally friendly energy mix), and the contribution of
36 the construction and operational phase to the overall environmental footprint of the system.

37 **Keywords:** impact assessment; inventory analysis; life cycle assessment; membrane
38 bioreactor; sensitivity analysis; urban wastewater

39 **1. Introduction**

40 In the last decade, MBRs have attracted a great deal of attention for the treatment of both
41 municipal and industrial wastewater (Trouve et al., 2014), with more than 2500 MBR
42 plants operating worldwide (Meng et al., 2012). The MBR technology features various
43 distinct advantages over the conventional activated sludge (CAS) process. Advantages
44 include the excellent effluent (i.e. permeate) quality, good disinfection capability
45 (membranes with small pore size), higher volumetric loading, reduced footprint and sludge
46 production, process flexibility towards influent changes and improved nitrification
47 (Hospido et al., 2012; Lin et al., 2014).

48 In addition, the occurrence of contaminants of emerging concern, including
49 pharmaceuticals (i.e. licit and illicit drugs) and personal care products in treated wastewater
50 and receiving waters is an issue which concerns conventional wastewater treatment. Drugs'
51 removal during CAS treatment occurs through various mechanisms, including
52 biodegradation (biotic process, mainly by bacteria and fungi), and abiotic transformations
53 (e.g. hydrolysis and sorption to biomass or suspended solids) (Cirja et al., 2008).
54 Biodegradation of drugs in CAS systems ranges from almost no biodegradation to high
55 biodegradation, depending on the type of microcontaminant and its biodegradability, but it
56 is far from complete biodegradation (Ternes et al., 2004). On the other hand, MBRs hold a

57 promise for more efficient or even complete degradation of some microcontaminants from
58 different water matrices, compared to the conventional biological systems; mainly due to
59 the high sludge concentration and relative high sludge age, at which they operate (Sipma
60 et al., 2010). More specifically, according to the scientific literature, MBR has been proved
61 to be a sufficient treatment technology for the removal of various licit and illicit drugs (i.e.
62 antibiotics, such as sulfamethoxazole, trimethoprim and clarithromycin, non-steroid anti-
63 inflammatory drugs, such as diclofenac, acetaminophen, ketoprofen and ibuprofen,
64 psychiatric drugs, such as carbamazepine and illicit drugs, such as cocaine and its
65 corresponding metabolites, such as benzoylecgonine) (Kimura et al., 2005; Bernhard et al.,
66 2006; Radjenovic et al., 2007; Reif et al., 2008; Shariati et al., 2010; Postigo et al., 2011;
67 Sahar et al., 2011).

68 Nevertheless, membrane fouling is still the main obstacle in the industrial application and
69 commercialization of MBR systems. Fouling reduces filtration performance and
70 membranes operational life, leading as a consequence to higher operating costs
71 (Rodriquez-Hernández et al., 2014) and energy demands. Elevated energy demands also
72 negatively affect the environmental sustainability of MBR systems

73 It is well known that MBR technology is an efficient wastewater treatment option that
74 produces an effluent with high quality. Among others, MBR-treated effluent can be safely
75 used for irrigation purposes. Nevertheless, MBRs' overall environmental sustainability
76 remains largely unknown and thus this study will try to shed light and give a better insight
77 on this, applying the LCA methodology.

78 Since the mid-1990s, the LCA method has proven its worth in the evaluation of the
79 environmental sustainability of water systems by using a whole system approach over their
80 entire life cycle, and by addressing all relevant types of environmental impacts from global
81 to local (Risch et al., 2014). Wastewater treatment has been studied using LCA analysis,
82 with various studies mainly focusing on: (i) comparisons and assessment of new treatment
83 technologies, in order to identify the most environmentally friendly ones (Vidal et al.,
84 2002; Foley et al., 2010), (ii) the identification of wastewater treatment plants' (WWTPs)
85 optimal operating conditions, pointing out their major environmental hotspots as
86 well(Clauson-Kaas et al., 2001, Hospido et al., 2004), and (iii) the integration of the

87 environmental vector at the design/construction phase of a WWTP, in order to optimize
88 the whole system from an environmental point of view (Page et al., 2011).

89 To the best of our knowledge, LCA has been applied to MBR systems only in a few cases
90 for treating urban wastewater (Tangsubkul et al. 2005; Ortiz et al. 2007; Pasqualino et al.,
91 2009; Hospido et al. 2012) and greywater (Memon et al. 2007). It should be highlighted
92 that the comparison of the results of different LCA studies, cannot be direct, since each
93 study has a different goal and scope definition, different impact assessment methods are
94 used, the assumptions made are not totally equivalent, while also the energy mix and the
95 geographical location of each study are different. Tangsubkul et al. (2005), compared
96 conventional wastewater treatment with additional microfiltration (CMF), MBR system
97 followed by reverse osmosis, and wastewater stabilization ponds (WSP)) in terms of their
98 environmental performance. The estimated scores, ordered from the highest to lowest were
99 WSP better than MBR better than CMF, for all impact categories, while the treatment
100 efficiency of MBR was significantly higher than WSP and CMF. In addition, in the study
101 of Memon et al. (2007), the environmental impacts of an MBR used for the treatment of
102 household greywater were compared with those of three other treatment technologies (i.e.
103 reed beds, membrane chemical reactor (MCR) and green roof recycling system (GROW)),
104 pointing out that the technologies based on natural treatment processes (i.e. GROW and
105 reed beds) have lower environmental impacts. Moreover, according to Ortiz et al. (2007),
106 both external and immersed MBR systems have shown lower environmental loads than a
107 CAS system followed by tertiary treatment, for the treatment of urban wastewater. In this
108 study electricity use, emissions of nutrients to the water, and application of sludge for
109 agricultural purposes were identified as the main impact contributors. A comparison of
110 four different MBR configurations was performed in the study of Hospido et al. (2012),
111 indicating that the main contributors to the environmental impacts were identical for all
112 four MBR configurations, with electricity consumption and agricultural application of
113 sewage sludge playing the most important role. Also, the environmental impacts of a
114 submerged anaerobic MBR (SAnMBR) system for the treatment of urban wastewater at
115 different temperatures (i.e. 20 and 33 °C), was assessed in a study by Pretel et al. (2013).
116 The LCA results revealed the importance of maximizing the recovery of nutrients, and thus
117 reducing the 'eutrophication' impact category by up to 50%, as well as the recovery of

118 dissolved methane, in order to obtain positive environmental impacts on 'toxicity' and
119 'freshwater aquatic ecotoxicity' impact categories.

120 From all the above, it can be concluded that existing literature is mainly focused on
121 environmental assessment and comparative analyses of new treatment technologies,
122 including MBR systems. The general conclusion is summarized to the fact that most of the
123 environmental impacts are traced back to the energy use. As a consequence, significant
124 environmental improvements are possible. However no measures for improving MBRs'
125 overall environmental sustainability have been systematically investigated. Moreover, the
126 environmental footprint of an MBR pilot unit treating urban wastewater containing targeted
127 antibiotic compounds is largely unknown. Thus, a comprehensive LCA study of the MBR
128 technology focusing on the identification of the majoring environmental hotspots,
129 including also sensitivity/improvement analyses in order to optimize the whole system
130 from an environmental point of view, is still missing.

131 This study uses the standardized LCA framework, as set in the International Organization
132 for Standardization (ISO) 14040:2006 and 14044:2006 (ISO, 2006 a,b), to quantitatively
133 define the inventory of resources consumed and estimate the emissions produced in an
134 MBR system used for the biological treatment of urban wastewater. According to the
135 authors' opinion, this is a first attempt to comprehensively assess the environmental
136 footprint and the main environmental hotspots of an MBR unit used for the treatment of
137 urban wastewater containing targeted antibiotic compounds. Also, this work includes a
138 sensitivity analysis and a life cycle improvement analysis of this treatment
139 technology which is a key element but still missing from the existing scientific literature.

140 **2. Methodology**

141 **2.1 Goal and scope definition**

142 The main objective of this work was to examine and assess the environmental sustainability
143 of an MBR pilot unit, used for the treatment of urban wastewater. A single- and a multi-
144 issue environmental impact assessment methods, namely IPCC 2013 and ReCiPe, were
145 employed. The former was used in order to better communicate results to non-academic

146 audiences and the latter to identify the impact categories (midpoint) and the areas of
147 protection (endpoint) that are affected by the MBR pilot unit.

148 **2.2 Functional unit**

149 The functional unit of this study is directly linked to the effective treatment of urban
150 wastewater and the removal of a specific antibiotic compound (i.e. sulfamethoxazole
151 (SMX)). Therefore, the functional unit that was chosen is the "effective treatment of 1 m³
152 of urban wastewater". It has to be noted that the effluent quality parameters that were
153 achieved at the optimum operational conditions were the removal of at least 67% of
154 effluents' COD (residual COD equal to 40 mg/L) and 82% of SMX (Table 1). It is
155 important to mention that the quality of the treated wastewater fulfills the quality criteria
156 of the Cypriot legislation (Regulation 772/2003) (i.e. COD: 125 mg/L and TSS: 35 mg/L),
157 in order to be safely reused for irrigation or to be disposed of in surface waters.

158 **2.3 System boundaries**

159 In Figure 1, the system boundaries of the MBR pilot unit are presented. These include the
160 construction materials, the MBR equipment, the treated effluent, as to its qualitative and
161 quantitative chemical characteristics, land use, other system outputs to the environment,
162 such as airborne emissions (i.e. from acidification and greenhouse gases (GHG)), the
163 transportation for construction and operation of the unit within the country, where it is
164 installed, and the effluent storage tank. The influent primary treatment (i.e. screening) and
165 the solid sludge waste (i.e. screened grit, removed solids) were not considered within the
166 scope of this LCA study and hence are not included in the system boundaries. This is
167 because a cradle-to-gate approach was used, i.e. the final disposal/reuse of the treated
168 effluent is outside of the system boundaries. The reason is that the route of the effluents'
169 disposal/reuse can affect the overall sustainability of the MBR system and therefore its
170 inclusion would make results valid for the specific route. For example, conventionally-
171 treated urban effluents are enriched with organic load, and therefore their reuse for field
172 irrigation can provide nutrient content (Bengtsson et al., 1997), lowering thus fertilizing
173 needs and in theory reducing the total environmental footprint. On the other hand, if these
174 effluents are directly released into a freshwater ecosystem they may impose stresses on the

175 'eutrophication' impact category, increasing thus the total environmental footprint, while
176 marine ecosystems are less sensitive to the eutrophication potential than the freshwater
177 ecosystems (e.g. rivers, lakes, etc.). Therefore, the route of disposal, as well as the local
178 conditions and technology used (e.g. piping, pumps, electricity mix, etc.) can have an effect
179 on the total environmental footprint, but this depends on too many local and specific
180 assumptions, which can limit the overall applicability of the results. Similarly, sludge
181 treatment and disposal were not considered within the system boundaries. Solid sludge
182 waste is the main by-product of the MBR pilot unit and as such it could be examined by a
183 separate LCA study. Moreover, different methods to manage the sludge exist, each one
184 with its own limitations, considerations and specific assumptions, and therefore each
185 method is expected to have its own environmental footprint. As a result, including a sludge
186 management scheme in this case study would limit the general relevance of the results
187 obtained by the present study.

188 Finally, a useful lifetime of 20 years for the MBR pilot unit was taken into account. This
189 is in line with relevant information in the literature (Emmerson et al., 1995; Vlasopoulos
190 et al., 2006) and also with the advice obtained by the manufacturer.

191 **2.4 Description of the MBR pilot unit**

192 The submerged membrane bioreactor considered in this study, consists of two
193 compartments: (i) the pre-aeration tank (mentioned as pre-aeration stage), where ammonia
194 nitrogen is converted to nitrates biologically through nitrification, and (ii) the membrane
195 bioreactor (mentioned as MBR stage), where the treated effluent permeates through flat-
196 sheet microfiltration (MF) membranes immersed in the bioreactor to a common manifold,
197 and then is stored in a final effluent tank (Schematic 1). The unit has a rectangular shape
198 (2.3 m x 1.4 m x 2.5 m), is made by stainless steel (SS304) and it is designed to treat 10 m³
199 day⁻¹ of primary-treated wastewater.

200 The screened wastewater flows through a pumping station, inside the MBR reactor, by a
201 self-priming feed pump of a capacity between 0.25 - 0.85 m³ h⁻¹, at 2 bar. A constant supply
202 of air provides content mixing and enhanced oxidation of organic carbon substances with
203 the use of two blowers (33 m³ h⁻¹) in pre-aeration tank and the MBR stage. The air blowers

204 are connected with four fine bubble diffusers in order to provide the surge of air inside the
205 MBR unit. The MBR consists of 25 flat-sheet cartridges (type FF25, Kubota) with a total
206 effective membrane surface area of 100 m². The nominal pore diameter of the membranes
207 is 0.4 µm, while the designed flux is 0.5 m³ m⁻² day⁻¹. The polymeric material of the
208 membrane structure is chlorinated polyethylene. The cleaning of the membranes is
209 conducted with sodium hypochlorite (NaClO) (0.5%), whilst for the treatment of 1 m³ of
210 wastewater 37.5 mg of NaClO is needed. The final effluent (permeate) passes to an
211 irrigation tank through a permeate pump controlled by a frequency converter. Finally, a
212 control panel completes the installation.

213 **2.5 Assumptions/Hypotheses**

214 The main hypotheses made for the MBR pilot unit operation are:

- 215 • According to standard practice, the MBR pilot unit works at full capacity (10 m³) all
216 year round.
- 217 • A useful life of 20 years is considered, as advised by the manufacturer.
- 218 • The motors that were chosen to be used for the construction of the pumps and the air
219 blowers LCI have a lifetime of 15 years, according to the available scientific literature
220 (Environmental Product Declaration, 2006).
- 221 • It is assumed that the unplasticized polyvinyl chloride (UPVC) pipes used in this study
222 have a lifetime of at least 50 years, and no replacement during the lifetime of the whole
223 unit is needed (Sand, 2013).
- 224 • Extraordinary conditions (i.e. flooding of the pilot plant, unexpected stoppage of the
225 units, etc.) were not considered (i.e. outside of the system boundaries).
- 226 • The transportation of the equipment needed for the installation of the MBR pilot unit is
227 assumed to be delivered from the city where it was constructed to the city where it was
228 installed (80 km distance). A truck (of approx. 7.5 tn) was considered for the equipment
229 transportation and installation, while vans (<2.5 tn, light vehicles) were selected for the
230 transportation of the chemicals and the maintenance of the normal function of the MBR
231 pilot unit. The average lifetime of these vehicles was assumed to be equal to 8.3 years,
232 according to the study of Erumban et al. (2008).

- 233 • The construction data (i.e. pieces of equipment of the plant, construction materials and
234 manufacturing processes) and the operation and maintenance data have been taken from
235 the Cypriot manufacturing company of the MBR pilot unit.
- 236 • The data regarding airborne emissions of MBR operation were taken from the available
237 scientific literature (Ortiz et al., 2007; Foley et al., 2010).

238 **3. Life Cycle Inventory (LCI) analysis**

239 An inventory of all flows (e.g. energy, raw materials and releases to air, land and water) of
240 the MBR system from and to nature was created. As part of this study, all relevant values
241 were normalized as per the functional unit, in order to make the options considered
242 comparable. Table 2 lists the Life Cycle Inventory (LCI) of the system under study. Data
243 external to the system boundaries are not included in the analysis. The attributional LCI
244 methodology was used, which by definition provides the set of total system-wide flows
245 that are “associated with” or “attributed to” the delivery of a specified amount of the
246 functional unit.

247 Experimental data regarding the MBR operation and treatment efficiency were collected
248 and used from the system itself. Data on materials and energy consumption, as well as
249 characterization of the wastewater entering and leaving the facilities were collected from
250 the Cypriot manufacturer of the unit, and on-site experiments and lab analysis that were
251 carried out. Also, the Ecoinvent 3.01 database was used to build the LCI of the MBR pilot
252 unit. Moreover, the local electricity mix, the electric motors and the submerge membranes
253 units were created from literature data, since they are not available in SimaPro’s LCI
254 datasets.

255 The electricity mix of Cyprus consists of 92.5% from oil, 5.6% from wind power, 1.1%
256 from photovoltaic systems and 0.8% from biomass (Electricity Authority of Cyprus, 2015).
257 Data from SimaPro’s LCI databases were used to model the aforementioned mix.

258 The types of the pumps and the air blowers used for the operation of the MBR pilot unit
259 are not available in the existing databases. For this reason a literature search was conducted,
260 and the available LCI data identified were related to the main part of this equipment,
261 namely to their motor. The motor that was chosen to be used in this LCA study was the

262 ABB Motor Type 90s (1.1 KW with a lifetime of 15 years) (Environmental Product
263 Declaration, 2006). The MBR pilot unit utilizes Kubota's submerged microporous
264 membranes (average pore size: 0.4 μm) cartridges, whose main material is chlorinated
265 polyethylene, which is not listed in existing LCI databases. Thus, it was compiled using its
266 main inputs, as described in the literature (Quenum et al., 1975; Dow Chemical Company,
267 2015). A useful life of five years was assumed for the membranes (Kubota, 2012). In
268 addition, the cleaning of the membranes is conducted with sodium hypochlorite (NaClO)
269 (0.5%), and it was estimated that in the lifetime of the MBR pilot unit (i.e. 20 years) a
270 quantity of 18.75 kg of NaClO is required.

271 **4. Life Cycle Impact Assessment**

272 Life Cycle Impact Assessment (LCIA) is the third phase of the LCA and consists of the
273 assessment and evaluation of the environmental impact of the system under study. In this
274 stage the data collected in the phase of LCI was assessed with the software package
275 SimaPro 8.0.3.14. SimaPro is one of the most widely known LCA tools, used both by
276 professionals and researchers (Foteinis et al., 2011). Two impact assessment methods were
277 used in this work, namely IPCC 2013 version 1.00 and ReCiPe version 1.10.

278 IPCC (Intergovernmental Panel on Climate Change) 2013 is a single issue method that
279 compares processes based on CO_2 emission equivalents ($\text{CO}_{2\text{-eq}}$), which are used to
280 measure the Global Warming Potential (GWP), a standard indicator of environmental
281 relevance that is easily understood by the public (Chatzisyneon et al., 2013). The standard
282 timeframe of 100 years was used in this work.

283 ReCiPe takes into account a broad set of environmental issues, including the GWP
284 indicator, and is a robust method that comprises two sets of impact categories (i.e. midpoint
285 and endpoint) with associated sets of characterization factors. At the midpoint level, 18
286 impact categories are addressed, i.e. 'climate change' (CC), 'ozone depletion' (OD),
287 'terrestrial acidification' (TA), 'freshwater eutrophication' (FE), 'marine eutrophication'
288 (MEP), 'human toxicity' (HT), 'photochemical oxidant formation' (POF), 'particulate matter
289 formation' (PMF), 'terrestrial ecotoxicity' (TET), 'freshwater ecotoxicity' (FET), 'marine
290 ecotoxicity' (MET), 'ionising radiation' (IR), 'agricultural land occupation' (ALO), 'urban

291 land occupation' (ULO), 'natural land transformation' (NLT), 'water depletion' (WD),
292 'metal depletion' (MD) and 'fossil depletion' (FD). These midpoint impact categories can
293 be multiplied by damage factors and aggregated into three endpoint categories (i.e. 'human
294 health, 'ecosystems' and 'resource surplus costs'), which in turn can be normalized,
295 weighted and aggregated into a single score (Chatzisyneon et al., 2013). ReCiPe, utilizes
296 three different perspectives, namely individualist (I), hierarchist (H) and egalitarian (E). In
297 this study, the H perspective was chosen for the evaluation of the results, since it is a
298 consensus model based on the most common policy principles, with regard to timeframe
299 and other issues.

300 **5. Results and Discussion**

301 For each of the two stages of the MBR pilot unit (i.e. pre-aeration stage and MBR stage),
302 a thorough LCI was performed, followed by a full LCA, in order to assess the
303 environmental impacts of each stage and identify their main hotspots. Finally, the two
304 stages were modeled together, in order to assess the total environmental footprint of the
305 entire MBR pilot unit.

306 **5.1 IPCC 2013 results**

307 The results of IPCC 2013 impact assessment method, for a timeframe of 100 years, are
308 presented herein. For the functional unit chosen in this case study, which is the effective
309 treatment of 1 m³ of urban wastewater, the total CO_{2-eq} emissions of the MBR pilot unit are
310 amount to 4.65 kg CO_{2-eq}/m³, while the contribution of each parameter (e.g. energy
311 consumption, pumps, membranes, maintenance activities, etc.) of the system to the total
312 GHG emissions is given in Figure 2.

313 As can be seen in Figure 2(a), the pre-aeration stage of the MBR pilot unit is responsible
314 for the 47.7% (i.e. 2.22 kg CO_{2-eq}/m³) of the total GHG emissions, while the remaining
315 52.3% (i.e. 2.43 kg CO_{2-eq}/m³) is attributed to the MBR stage of the unit. The majority of
316 the CO_{2-eq} emissions (i.e. 97% or 4.52 kg CO_{2-eq}/m³) is traced back to the energy used by
317 the lift pump and the air blower in the pre-aeration stage and the air feeding and the
318 permeate pump in the MBR stage. This especially high contribution (i.e. 97%) can be
319 attributed to two main reasons: (i) the local energy mix, which is heavily depended on fossil

320 fuels, and (ii) the overall low contribution to the total CO_{2-eq} emissions of the equipment
321 and materials used for the construction of the unit. As far as the energy consumption is
322 concerned, the use of oil accounts by itself for 95.5% of the total CO_{2-eq} emissions, while
323 wind power, biomass and solar energy are responsible for 0.1%, 0.4% and 1%, respectively
324 (Figure 2(b)). The small contribution of the latter is attributed to the facts that these are
325 renewable energy sources and as such have a minimal environmental impact, and they only
326 contribute by a very small percentage to the local electricity mix. Moreover, 0.6% (or 0.029
327 kg CO_{2-eq}/m³) is attributed to the submerge membrane units, 0.8% (or 0.038 kg CO_{2-eq}/m³)
328 to the pre-fabricated tank (manufacturing procedure and production material (i.e. stainless
329 steel)), while the maintenance activities of the unit contribute 0.85% to the total CO_{2-eq}
330 emissions. It has to be noted that the airborne emissions and the land use of the MBR pilot
331 unit have a few orders of magnitude lower CO_{2-eq} emissions, compared to the energy
332 consumption, and thus they are considered as negligible. This is attributed to the fact that
333 airborne emissions, which are mainly direct CO_{2-eq} emissions, were assumed to be
334 biogenic, having thus a neutral impact on the environment. In addition, the use of chemicals
335 for membrane cleaning and prevention of membrane fouling has a negligible contribution
336 to the total environmental impact, due to the small amounts used and their low
337 environmental impacts (e.g. NaOCl). Moreover, the pumps, the aeration diffuser, the air
338 feeding and the pipes exhibit a very low contribution (<0.1%) to the total CO_{2-eq} emissions.
339 It is noted that the latter refers to the environmental impact of the material production of
340 the above mentioned equipment.

341 It should be highlighted that the construction phase of the MBR unit has a minimal
342 environmental impact (~3.5%), compared to the operational phase (~96.5%), mainly due
343 to the fact that: (i) the materials used for the construction of the MBR pilot unit, except of
344 the membrane units, are not associated with high environmental impacts, (ii) these
345 materials exhibit an overall high life span, and (iii) recycling of the main materials (i.e.
346 stainless steel and plastics), after the end of the lifespan of the pilot unit, was considered
347 (i.e. a 70% recycling on metals/plastics was assumed). It should be noted though that the
348 fossil fuel-dependend grid, used in this study, contributes to the increase of the
349 environmental impacts of the operational phase of the unit.

350 The mean daily CO_{2-eq} emissions per capita in Cyprus are about 27.7 kg CO_{2-eq} (data for
351 2013) (EEA, 2014), and the daily treated urban wastewater per capita in Cyprus is about
352 50 L (data for 2009) (AQUASTAT, 2013). Comparing the treatment of the wastewater
353 effluent per capita in Cyprus by an MBR unit, it is obvious that its emissions would
354 contribute less than 1.2% of the mean daily total CO_{2-eq} emissions per capita. This low
355 contribution illustrates the sustainability of the MBR technology for treating urban
356 wastewater effluents.

357 **5.2 ReCiPe results**

358 The ReCiPe impact assessment method was employed, in order to identify the midpoint
359 and endpoint impact categories that are affected by the MBR operation, as well as its total
360 environmental footprint. Figure 3, shows the contribution of each parameter of the MBR
361 pilot unit at each of the 18 midpoint impact categories mentioned above. It is shown that
362 the majority of the environmental impacts is attributed to the lift pump, air blower (pre-
363 aeration stage), air feeding and the permeate pump (MBR stage). Similarly to IPCC 2013,
364 this is attributed to the consumption of energy, and specifically to the fossil fuel-dependent
365 electricity mix used herein. The submerge membrane unit contributes to a lower extent to
366 the toxicity impact categories (i.e. 'terrestrial ecotoxicity', 'human toxicity' and 'marine
367 ecotoxicity').

368 Figure 4, shows ReCiPes' 18 midpoint level normalized impact categories, using Europe's
369 reference inventories. ReCiPes' score is expressed in Eco-Indicator points (Pt), where 1000
370 Pt is the yearly environmental load of an average European citizen. As shown, the impact
371 categories that are affected the most, from the higher to the lower score, are: 'natural land
372 transformation', 'marine ecotoxicity', 'human toxicity', 'freshwater ecotoxicity' and
373 'terrestrial acidification'. These impact categories are mainly affected by the energy
374 consumption of the pumps and blowers of the MBR unit, and more specifically by the
375 crude oil extraction and refining and from the combustion of oil, which is the main energy
376 source of the local grid. For example, fossil fuel combustion release toxic materials, such
377 as heavy metals, sulphurous compounds and polycyclic aromatic hydrocarbons (PAHs) to
378 the environment, affecting thus the 'ecotoxicity' (e.g. marine and freshwater ecotoxicity)
379 and 'toxicity' (e.g. human toxicity) impact categories (Atilgan and Azapagic, 2015).

380 Moreover, fossil fuel extraction, transportation and processing can require large areas,
381 therefore affecting the impact category 'natural land transformation'. Furthermore, the
382 impact categories 'fossil depletion', 'particulate matter formation', 'photochemical oxidant
383 formation' and 'climate change' are affected to a lower extent, as shown in Figure 4. This
384 is mainly due to the fossil fuel combustion. The impact categories 'freshwater
385 eutrophication' and 'terrestrial ecotoxicity' are mainly affected by the extraction process
386 (e.g. the impact on freshwater is due to phosphate emissions from fossil fuel extraction and
387 nitrogen oxide emissions from combustion) (Atilgan and Azapagic, 2015). The remaining
388 impact categories have a very low score and thus they are assumed to be negligible.

389 Moreover, as shown in the inset graph of Figure 4, the membrane units have a very low
390 contribution, compared to the electricity consumption, and is mainly attributed to the
391 impact categories 'terrestrial ecotoxicity' and 'human toxicity', while they also exhibit a
392 smaller contribution to the impact categories 'fossil depletion', 'marine ecotoxicity',
393 'freshwater ecotoxicity', 'particulate matter formation', 'terrestrial acidification' and 'climate
394 change'. The materials of the membranes (i.e. chlorinated polyethylene and ABS resin),
395 which according to the study of DeMatteo, (2011) are suspected as carcinogenic,
396 contributed to these impact categories. Specifically, the manufacturing procedure of
397 chlorinated polyethylene, which is based on the chlorination of polyethylene by gaseous
398 chlorine, contributes to these impact categories. According to the Material Safety Datasheet
399 (MSDS) of chlorinated polyethylene resin, at temperatures exceeding melt temperatures,
400 polymer fragments can be released, while its decomposition products can include among
401 others aldehydes, alcohols, organic acids, hydrogen chloride, as well as trace amounts of
402 hydrocarbons (Dow Chemical Company, 2014). The construction of the pre-fabricated
403 tank contributes to a lower extent to the impact categories 'metal depletion' (mainly due to
404 the raw material (i.e. stainless steel) that is constructed from), 'particulate matter formation',
405 'terrestrial acidification', 'fossil depletion' and 'climate change', while the air diffuser used
406 in the pre-aeration stage of the MBR pilot unit contributes mainly to 'marine ecotoxicity',
407 'freshwater eutrophication', 'freshwater ecotoxicity' and 'human toxicity'. Moreover, the
408 land use and the maintenance activities of this unit contribute mainly to the impact
409 categories 'fossil depletion' and 'human toxicity'. Finally, the chemical cleaning of the MBR
410 exhibits a very low, almost negligible score on all impact categories, as shown in Figure 4,

411 which can be attributed to the small amounts of chemicals used for the cleaning of this unit
412 and to the fact that the chemicals (i.e. NaOCl) used (i.e. production, application and
413 disposal) are not associated with a high environmental footprint.

414 From all the above, it can be concluded that the aforementioned midpoint impact categories
415 are mainly affected by indirect emissions from oil extraction and electricity production and
416 are not the result of direct emissions from wastewater treatment by the MBR pilot unit.
417 This is in line with the study of Slagstada and Brattebø, (2014). Therefore, if electricity is
418 provided by an environmentally friendly renewable energy source, such as solar energy,
419 different impact categories would be affected and lower normalized scores would be
420 expected, highlighting thus the need for a sensitivity analysis.

421 Figure 5 shows the aggregated environmental impacts of the MBR pilot unit, using
422 ReCiPes' three endpoint indicators (i.e. 'human health', 'resources' and 'ecosystems').
423 According to this figure, the total environmental footprint of the MBR pilot unit is 442 mPt
424 per treated m³ of urban wastewater with the damage category 'human health' exhibiting the
425 highest score (195 mPt), followed by 'resources' (161 mPt), while 'ecosystems' damage
426 category has the lowest score (85 mPt). Similarly, to the midpoint analysis the main
427 contributor to these damage categories is the electricity consumption from the local energy
428 mix, i.e. energy consumption being responsible for 0.4 Pt. 'Human health' damage category
429 is affected by the extraction process and oil combustion (e.g. airborne emissions), while
430 'recourses' damage category is affected by the depletion of crude oil, a non-renewable
431 energy source.

432 The results of this study are in agreement with Tangsubkul et al. (2005), Memon et al.
433 (2007), Hospido et al. (2012) and Pretel et al. (2013), where the main contributor to all
434 impact categories (e.g. global warming, eutrophication, freshwater aquatic ecotoxicity,
435 terrestrial ecotoxicity, etc.) was also the energy consumption of the MBR unit. Also,
436 Memon et al. (2007) and Ortiz et al. (2007) noted that the operational phase of an MBR
437 contributes the most (about 95% and 79%, respectively) compared to the construction
438 phase (about 5% and 21%, respectively) for the treatment of greywater and urban
439 wastewater, respectively. These values are in line with the results of the present study (i.e.
440 96.5% operational and 3.5% construction phase).

441 **6. Alternative Scenarios - Sensitivity analysis**

442 In terms of the total environmental footprint, the MBR pilot unit was found to yield low,
443 but still important, environmental impacts. Thus, alternative scenarios to improve its
444 sustainability were examined.

445 A sensitivity analysis was conducted in order to determine how changes in the main
446 environmental hotspots, i.e. energy mix and material of the membrane units, were affecting
447 the overall sustainability of the MBR pilot unit. For this reason, four different energy
448 mixes, namely Greek (Grid 2), Italian (Grid 3), French (Grid 4) and Norwegian (Grid 5)
449 were compared to the Cypriot energy mix (Grid 1). Their effects on GHG emissions and
450 on the overall environmental footprint of the MBR pilot unit were also examined. Grid 2
451 is heavily depended on fossil fuels (i.e. 54% provided by solid fuels (lignite), 11% on crude
452 oil, 17% on natural gas, while 18% is provided by renewable energy sources) (Public
453 Power Corporation S.A. Hellas, 2015). Although lignite is a 'cheap' energy source, the
454 environmental impacts associated with its use are high, something that applies also for
455 petroleum and in a lower extent for natural gas (Theodosiou et al., 2014). Grid 3 is also
456 based on fossil fuels (51%), but in this case natural gas, a much cleaner fossil fuel compared
457 to lignite and crude oil, which accounts for 39% of the energy mix, and a further 10% by
458 renewable energy sources (European Union, 2013). In the case of Grid 4, 76% of electricity
459 is provided by nuclear power, while the remaining 15% is provided by renewable energy
460 sources and 9% by fossil fuels (French National Grid, 2015). Finally, Grid 5 is based on
461 renewable energy sources (i.e. 97.9% hydroelectric, 1.5% thermal and 0.6% nuclear),
462 exhibiting thus a very environmentally friendly footprint. Moreover, due to the fact that
463 globally the energy mix is heavily depended on fossil fuels - and more specifically,
464 according to the study of Theodosiou et al. (2014), 80% of the electricity needs worldwide
465 are met by fossil fuels - a renewable energy source, namely solar energy, the most abundant
466 renewable source in the country, was also examined. Finally, a more environmentally
467 friendly membrane material, namely ethylene propylene diene monomer (EPDM), was
468 examined, assuming that an EPDM membrane would have the same treatment performance
469 as chlorinated polyethylene membrane, which was used in the conventional scenario.

470 **6.1 Life Cycle Improvement Analysis of the MBR pilot unit using solar energy**

471 The first and most critical improvement that can be made for the system under study is the
472 diversification of the electricity mix, the main environmental hotspot. Usually, high energy
473 consumption for the operation of a WWTP comes with the benefit of achieving high
474 effluent quality, although this is accompanied by a high environmental cost (Ortiz et al.
475 2007). On this basis, if reducing the energy consumption is not possible, then the option of
476 shifting to a cleaner energy source (i.e. solar) could be examined, as to improve the
477 environmental performance of the applied technology.

478 In the first alternative scenario (S1), the energy needs of the MBR pilot unit are covered
479 100% by solar energy originating from a photovoltaic (PV) system that is connected to the
480 electrical grid. It was shown that the use of solar energy can substantially reduce the total
481 GHG emissions (IPPC 2013) of the MBR pilot unit, since the total CO_{2-eq} emissions are
482 reduced from 4.65 kg CO_{2-eq}/m³ (conventional scenario) to 0.56 kg CO_{2-eq}/m³, i.e. 88%
483 reduction. Moreover, in S1 the contribution of electricity consumption to the total GHG
484 emissions is 75.2%, the maintenance activities 7%, the submerge membrane units 5.2%,
485 the pre-fabricated tank of the unit 6.85% and the pumps 1.7%. It is noted that the latter
486 percentage (i.e. 1.7%) refers to the environmental impact of the material production of the
487 pumps. Therefore, not only do the total GHG emissions of the MBR unit are substantially
488 reduced (i.e. by 88%), but the contribution of the construction and the operation phase to
489 the total GHG emissions, during the whole lifespan of the MBR pilot unit, is also
490 significantly affected.

491 When ReCiPe impact assessment method is used, the environmental footprint of the MBR
492 pilot unit is again significantly reduced through the use of solar energy. In this case, the
493 most affected impact categories are the ecotoxicity/toxicity ones, which are attributed to
494 the manufacturing procedure of the PV panels that results to airborne emissions, mainly
495 copper, and to the high amounts of fossil fuels that are used during the manufacturing
496 procedure of the PV, which also induce impacts onto the damage category 'human health'.
497 Specifically, the high normalized scores on the impact categories 'freshwater ecotoxicity'
498 and 'marine ecotoxicity' are largely attributed to the emissions of metals during PV panels
499 manufacturing procedure. These emissions, can induce significant changes in metal
500 concentrations on freshwater and marine ecosystems (Mohr et al., 2009).

501 When ReCiPe results are aggregated into a single score, the total environmental footprint
502 of S1 is 74.7 mPt, instead of 442 mPt in the conventional scenario. Thus, a substantial
503 reduction, about 83%, is achieved by adopting solar energy. Moreover, the damage
504 category 'human health' is affected the most, followed by the 'resources' and 'ecosystems'.
505 Life-cycle emissions could derive from fossil fuel-based energy consumption to produce
506 the materials for solar cells, modules and systems, as well as directly from smelting,
507 production and manufacturing facilities. Indirect emissions associated with the use of fossil
508 fuels in the generation of energy required in the life cycle of photovoltaics can result to
509 heavy metal, SO_x, NO_x, particulate matter (PM), CO₂, toxic gas and GHG emissions.
510 Direct emissions include particulate matter and heavy metals from mining and smelting,
511 whereas liquid and solid waste are, for the most part, being recycled according to the study
512 of Fthenakis et al. (2008). These indirect emissions (e.g. heavy metal, SO_x, NO_x, PM, CO₂,
513 toxic gas), as well as the direct heavy metal emissions mainly affect the damage category
514 'human health', whereas the damage category 'resources' is mainly affected by raw
515 materials and fossil fuel consumption for the PV production. Finally, the damage category
516 'ecosystems' is mainly affected by heavy metal emissions.

517 **6.2 Life Cycle Improvement Analysis of the MBR pilot unit using EPDM membranes**

518 In the second alternative scenario (S2) the effect of the use of a more environmentally
519 friendly membrane material (i.e. ethylene propylene diene monomer (EPDM)), compared
520 to the material used in the conventional scenario, (i.e. chlorinated polyethylene) was
521 examined. EPDM is an inert material with limited environmental impact during
522 manufacturing, installation and use, while its excellent performance reflects to low life
523 cycle costs and less impact on the environment. If the membrane material is to be
524 substituted by EPDM, it is found that it can reduce the membrane unit contribution to the
525 total GHG emissions (IPCC 2013) almost by half. Nonetheless, this reduction does not
526 significantly affect the total GHG emissions of the MBR pilot unit, since the membrane
527 units contribution is reduced from 0.81% to 0.44%. Moreover, as far as the total aggregated
528 environmental impact (ReCiPe) is concerned, the substitution of the membrane material
529 has a slight effect, less than 1% reduction, on the overall sustainability of the MBR pilot

530 unit. It has to be noted again that it was assumed that EPDM membranes would have the
531 same treatment performance as the membrane made by chlorinated polyethylene.

532 **6.3 Sensitivity analysis of the MBR pilot unit using different energy mixes**

533 The choice of the electricity mix is a key aspect when assessing the environmental
534 sustainability of a wastewater treatment technology. Therefore a sensitivity analysis was
535 conducted in order to determine the effect of energy mix diversification on the
536 sustainability of the MBR unit. Apart from the Cypriot energy mix (Grid 1), the Greek
537 (Grid 2), Italian (Grid 3), French (Grid 4), Norwegian (Grid 5) as well as solar energy (Grid
538 6) utilization, were examined.

539 When solar energy is utilized (Grid 6), then the GHG emissions are significantly reduced
540 to 0.556 kg CO_{2-eq}/m³ (from 4.65 kg CO_{2-eq}/m³ in the conventional scenario), as mentioned
541 above. The reason is that PV technologies generate far less life-cycle air emissions per
542 GWh than conventional fossil-fuel-based electricity generation technologies. Fthenakis et
543 al. (2008), noted that at least 89% of air emissions associated with electricity generation
544 could be prevented if electricity from photovoltaics displaces electricity from the grid,
545 which is in accordance with the findings of this study (88% reduction of GHG emissions).
546 When Grid 2 is used, the total GHG emissions are slightly elevated, compared to the
547 conventional scenario, and amount to 5.70 kg CO_{2-eq}/m³. This increase is attributed to the
548 nature of this grid (Grid 2), which is depended on lignite, a less environmentally friendly
549 choice compared to oil used in Grid 1 (Theodosiou at al., 2014). When Grid 3 is used, a
550 reduction of about 26% compared to the conventional scenario (Grid 1), is observed, which
551 is mainly attributed to the use of natural gas, a more environmentally friendly solution than
552 oil (Theodosiou at al., 2014), and to the higher contribution of renewable energy sources.
553 Moreover, the effect of nuclear power, which is not a renewable source, was examined by
554 using Grid 4 as input. In this case, a sharp reduction (84%) on the total GHG emissions is
555 observed, since only 0.73 kg CO_{2-eq}/m³ are emitted, but this is still higher than that emitted
556 in the case of Grid 6 (0.556 kg CO_{2-eq}/m³). When Grid 5 is used, then the MBR pilot unit
557 achieves the highest sustainability, since the total GHG emissions are only 0.25 kg CO₂₋
558 eq/m³. Hydropower is the most environmentally friendly energy source and thus a reduction
559 of about 94.5% is observed on the total GHG, compared to the conventional scenario (Grid

560 1), and 50% compared to Grid 6. A comprehensive overview of the total GHG emissions
561 per energy mix for the treatment of 1 m³ of urban wastewater by the MBR pilot unit is
562 presented in Figure 6. As shown in Figure 6, the higher environmental footprint of solar
563 energy, when compared to hydroelectricity, is attributed to the energy and materials
564 required for PV system's module production (Fthenakis et al., 2008).

565 When the ReCiPe impact assessment method was used, then the results differed, since not
566 only the total environmental footprint was found to be affected by the type of each energy
567 mix but also the scores of the impact and the damage categories varied significantly. In
568 Figure 7 (a) the normalized scores, at midpoint level, for the treatment of 1 m³ of
569 wastewater by means of the MBR pilot unit, using different energy mixes, are presented.
570 As shown, each energy mix affects a different impact category, with the case of Grid 5
571 exhibiting overall lower scores and the case of Grid 2 overall higher scores. As noted
572 above, most of the impact categories are mainly affected by indirect emissions that relate
573 to the electricity generation, thus the differences in the energy mixes are reflected in the
574 different scores on each impact category.

575 Moreover, in order to compare each energy mix at endpoint level, the results were
576 aggregated into ReCiPe's three damage categories and then compared by using a single
577 score. Specifically, in Figure 7 (b), ReCipe's three damage categories (i.e. 'human health',
578 'ecosystems' and 'resources') and the contribution of each energy mix is presented. As
579 observed, the damage category that is mainly affected by the MBR pilot unit is the category
580 'human health' followed by 'resources'. This is attributed mainly to the airborne emissions
581 from fossil fuel extraction and electricity production by the different energy mixes used,
582 while also air- and water-borne emissions from the same procedure mainly affect the
583 damage category 'ecosystems'.

584 As far as the total aggregated environmental footprint is concerned, Grid 1, Grid 2, Grid 3,
585 Grid 4 and Grid 5 amount to 0.42, 0.66, 0.31, 0.083 and 0.034 Pt/m³, respectively.
586 Therefore energy mixes that are heavily depended on fossil fuels, such as Grid 2 and Grid
587 1, highly affect the sustainability of the MBR system. For example, in the conventional
588 scenario the total environmental footprint of the MBR pilot unit is 13-fold higher than those
589 of Grid 5, where electricity is provided by renewable energies, and 5.4-fold higher than the

590 case of nuclear power (i.e. Grid 4). Therefore, it is concluded that the progressive
591 substitution of fossil fuels by renewable energies (i.e. Grid 5 and Grid 6), provokes an
592 important reduction of the environmental load. The results of this study are also in
593 agreement with the study of Ortiz et al. (2007), where the airborne emissions of an
594 immersed and an external MBR system were found to significantly depend on the different
595 origins of electricity.

596 **7. Conclusions**

597 Results indicate that the majority of the environmental impacts of the MBR pilot unit were
598 attributed to indirect emissions, tracing back to electricity consumption. This is in line with
599 existing literature. The second main contributor to the total environmental footprint was
600 identified to be the membrane units. Nonetheless, due to their high life expectancy, they
601 have only a low contribution to the total environmental footprint. It should be highlighted
602 that the total GHG emissions of this unit operated for the treatment of 1 m³ of urban
603 wastewater correspond to approximately 1% of the daily GHG emissions per capita,
604 demonstrating thus the systems' environmental sustainability. A sensitivity analysis
605 revealed that when fossil fuel depended electricity mixes, such as oil and/or lignite, were
606 used for the MBR pilot unit operation, high life-cycle footprints were observed, due to the
607 extraction and burning of fossil fuels, which releases pollutants and carbon dioxide to the
608 environment. If electricity from renewable energy sources, such as solar (which is an
609 abundant energy resource in the Mediterranean countries) and/or hydroelectricity, replaces
610 fossil fuels, the environmental footprint of the MBR pilot unit could be significantly
611 reduced even up to 13-fold compared to the conventional scenario. Therefore, the
612 environmental impact and the overall sustainability of the MBR system are highly
613 depended on the different origins of the electricity consumed. However, in all cases
614 examined the life-cycle emissions of the MBR pilot unit were not the result of direct
615 emissions from the wastewater treatment applied, but from indirect emissions attributed to
616 the energy production and/or material production.

617

618

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Table 1: Quantitative characteristics of MBR influent and effluent

Parameters	MBR influent	MBR effluent
pH	7±0.5	6.7±0.4
Conductivity ($\mu\text{S cm}^{-1}$)	1322±100	1003±95
DO (mg/L)	5.6±0.4	4.3±0.5
COD (mg/L)	120±12	40±7
TOC (mg/L)	42.7±5	8.8±0.9
TSS (mg/L)	42000±553	10±0.8
SMX ($\mu\text{g/L}$)	18.2±2	3.3±0.2

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Table 2: Life Cycle Inventory (LCI) of the MBR pilot unit.

Experimental setup configuration		Useful lifetime (years)
Prefabricated tank (<i>material: stainless steel, Fe/Cr₁₈/Ni₁₀</i>)	800 kg	20
Two pumps (feed and permeate) _ 0.75 kW (<i>material: cast iron GG25 with flake graphite</i>)	35 kg each one	15
Basket screen (<i>material: stainless steel, Fe/Cr₁₈/Ni₁₀</i>)	6 kg	20
Two air blowers _ 1.1 kW (<i>material: aluminum alloy</i>)	32 kg each one	30
Four air diffusers (<i>material: membrane high grade EPDM</i>)	2 kg each one	8
Four support discs (<i>material: PVC (polyvinyl chloride)</i>)	2 kg each one	8
Submerge membrane unit (25 membrane cartridges) (<i>material: chlorinated polyethylene; ABS resin membrane</i>)	3 kg each one	5
Flow indicator (<i>material: polysulphone</i>)	3 kg	30
Membrane case (<i>material: stainless steel, Fe/Cr₁₈/Ni₁₀</i>)	65 kg	20
Pipes (<i>material: UPVC PE</i>)	13.44 kg	50
Chemical cleaning (0.5% sodium hypochlorite (NaClO))	18.75 kg during the lifetime of the MBR unit (i.e. 20 yr)	-
Energy requirements		
Energy from the Cypriot grid (medium voltage)	92.5% oil, 5.6% wind power, 1.1% photovoltaic systems and 0.8% biomass	-
kWh for the treatment of 1 m ³ of urban wastewater per day	5.36 kWh m ⁻³	-
Local transportation		
Delivery and installation (by truck 8.8 tn)	5632 km	8.3
Maintenance (by van 2.7 tn)	25920 km	8.3
Outputs to nature (per functional unit)		
Airborne emissions MBR (Data provided from: Ortiz et al., (2007) and Foley et al., (2010))		
CO ₂	0.77 Kg CO ₂ m ⁻³	-
SO _x	2.79 g SO _x m ⁻³	-
NO _x	1.40 g NO _x m ⁻³	-
NMVOG	0.46 g NMVOG m ⁻³	-
Dust	0.72 g dust m ⁻³	-

766

767 **Figure Captions**

768 **Schematic 1: Flow diagram of the MBR pilot unit.**

769 **Figure 1:** System boundaries of the MBR pilot unit LCA.

770 **Figure 2:** (a) Dendrogram of the main parameters and their contribution to the total CO₂-
771 eq emissions of the MBR pilot unit, using the IPCC 2013 methodology for a timeframe of
772 100 years and 0.5% cut-off; and (b) circular statistical graphic illustrating the contribution
773 of each parameter of the MBR pilot unit to the total environmental footprint. The arc length
774 of each slice is proportional to the percentage (%) it represents.

775 **Figure 3:** %Contribution of each parameter of the MBR pilot unit to the midpoint impact
776 categories, according to the ReCiPe methodology.

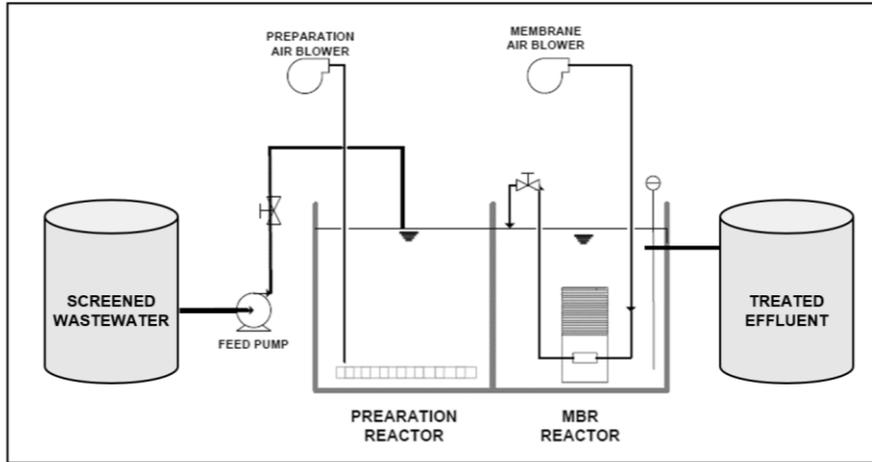
777 **Figure 4:** ReCiPe's normalized results for the treatment of 1 m³ of urban wastewater by
778 means of the MBR pilot unit.

779 **Figure 5:** ReCiPe's aggregated endpoint impact categories for the treatment of 1 m³ of
780 urban wastewater by the MBR pilot unit.

781 **Figure 6:** Total GHG emissions (IPCC 2013) of the MBR pilot unit using the different
782 energy mixes examined in this study.

783 **Figure 7:** ReCiPe's (a) normalized midpoint level impact categories and (b) aggregated
784 environmental endpoint level impacts of the MBR pilot unit for the different energy mixes
785 examined in this study.

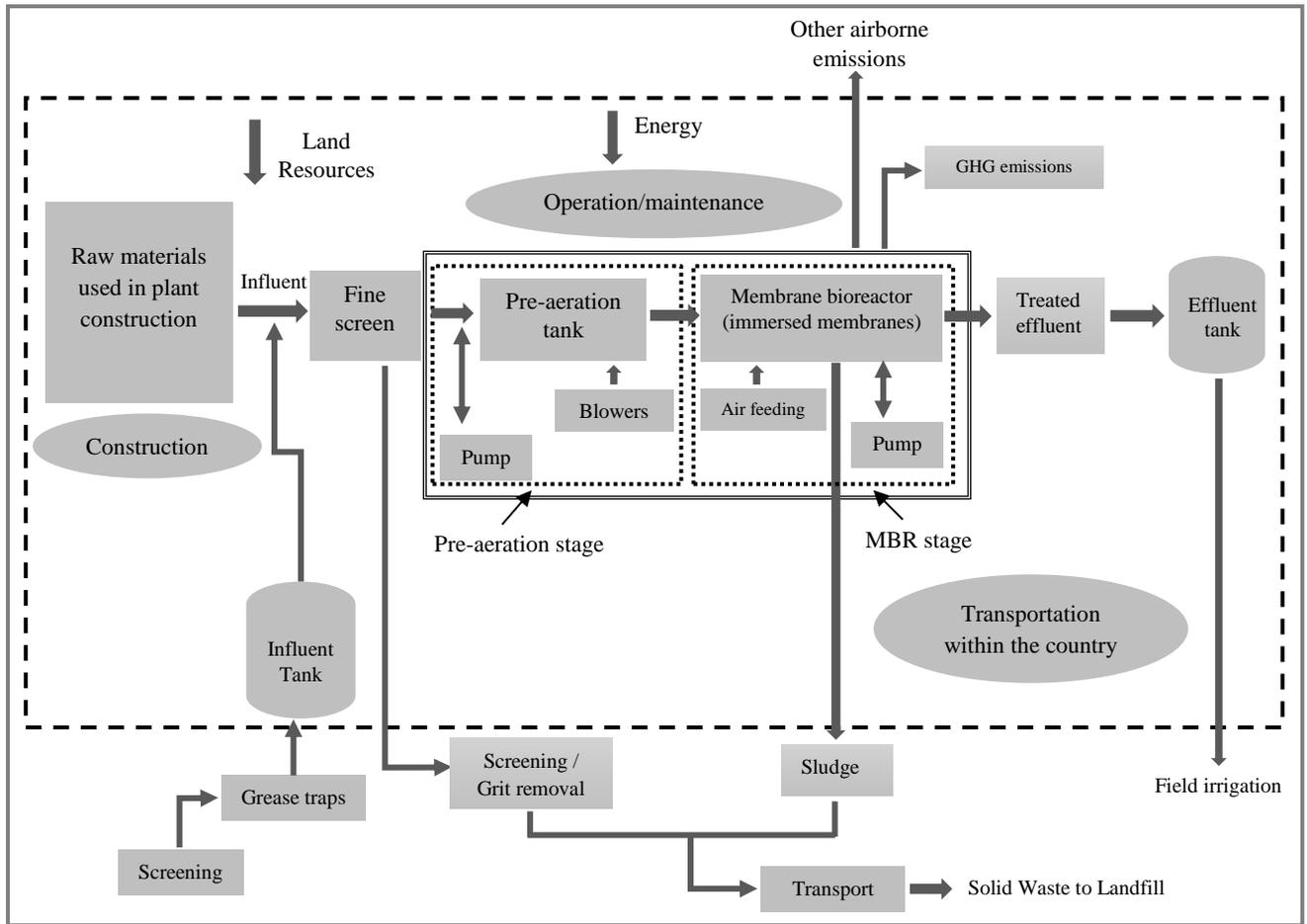
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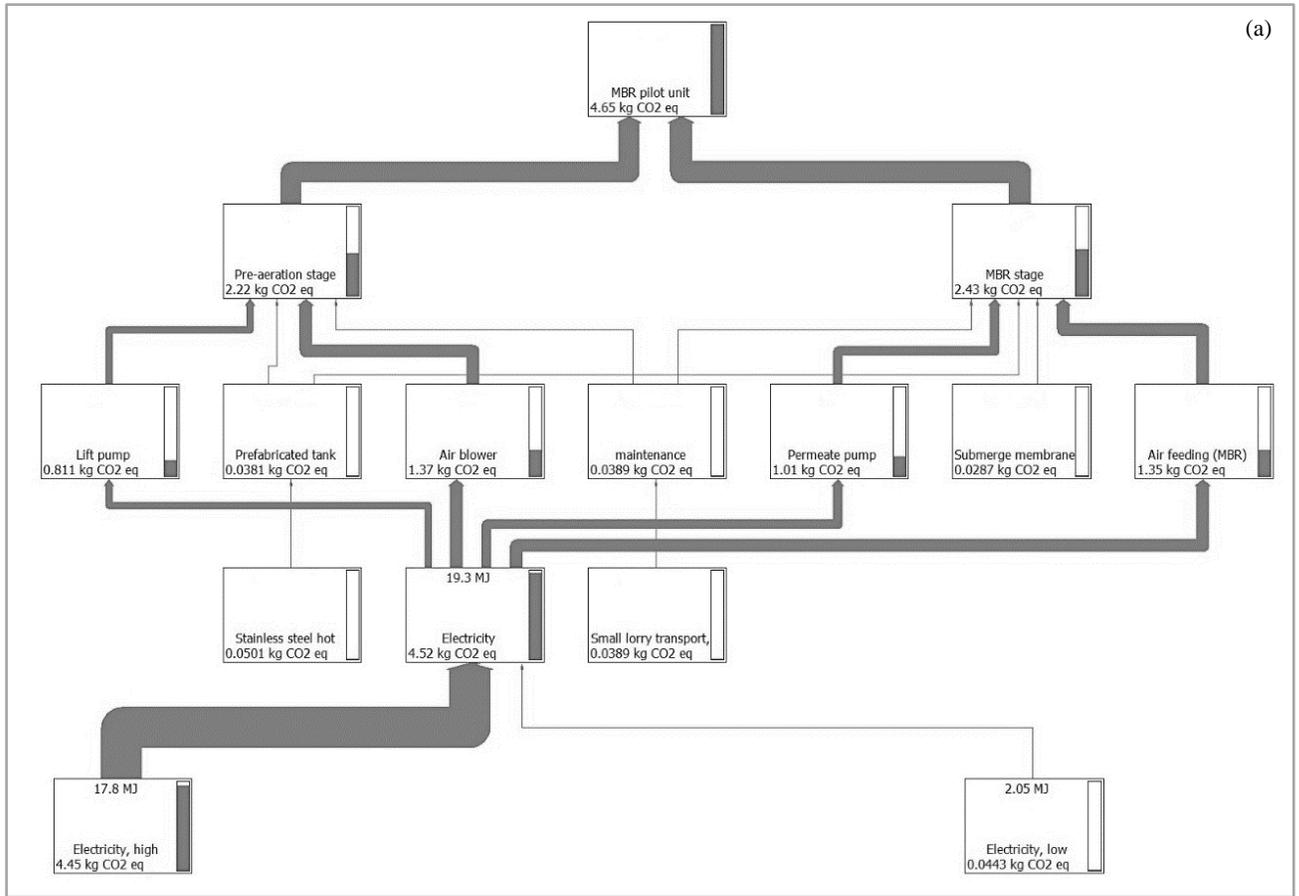
Schematic 1



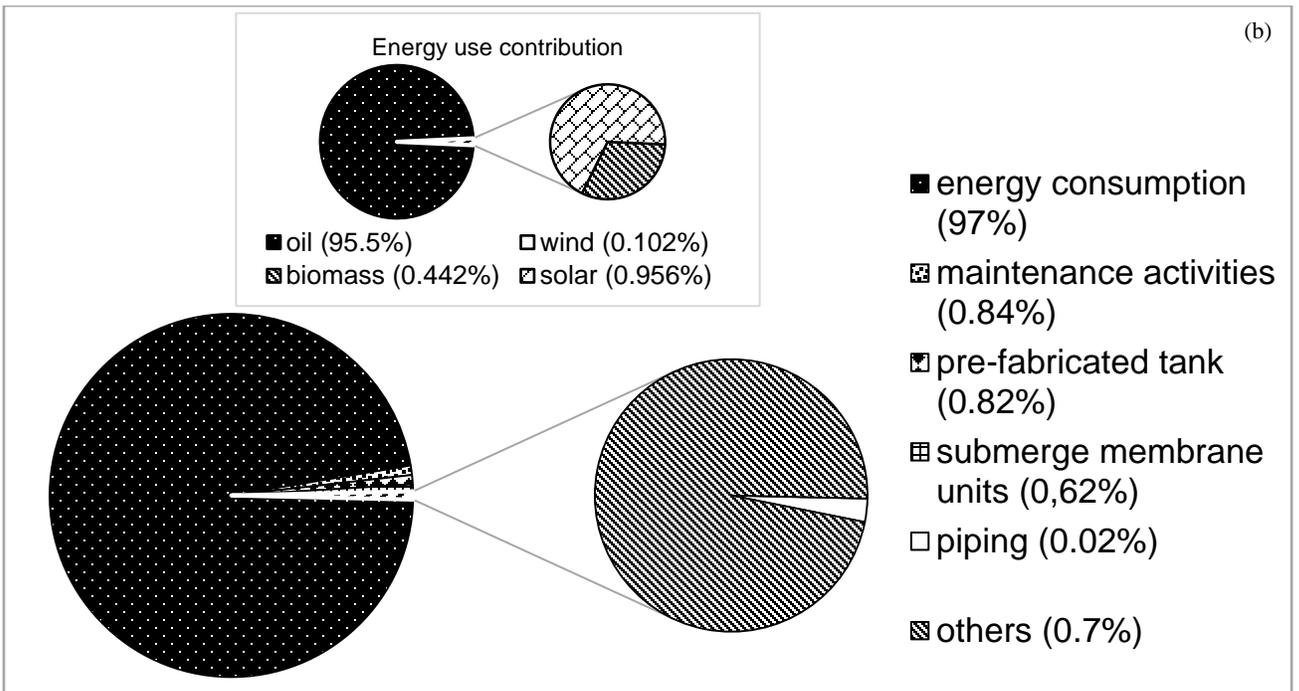
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Figure 1



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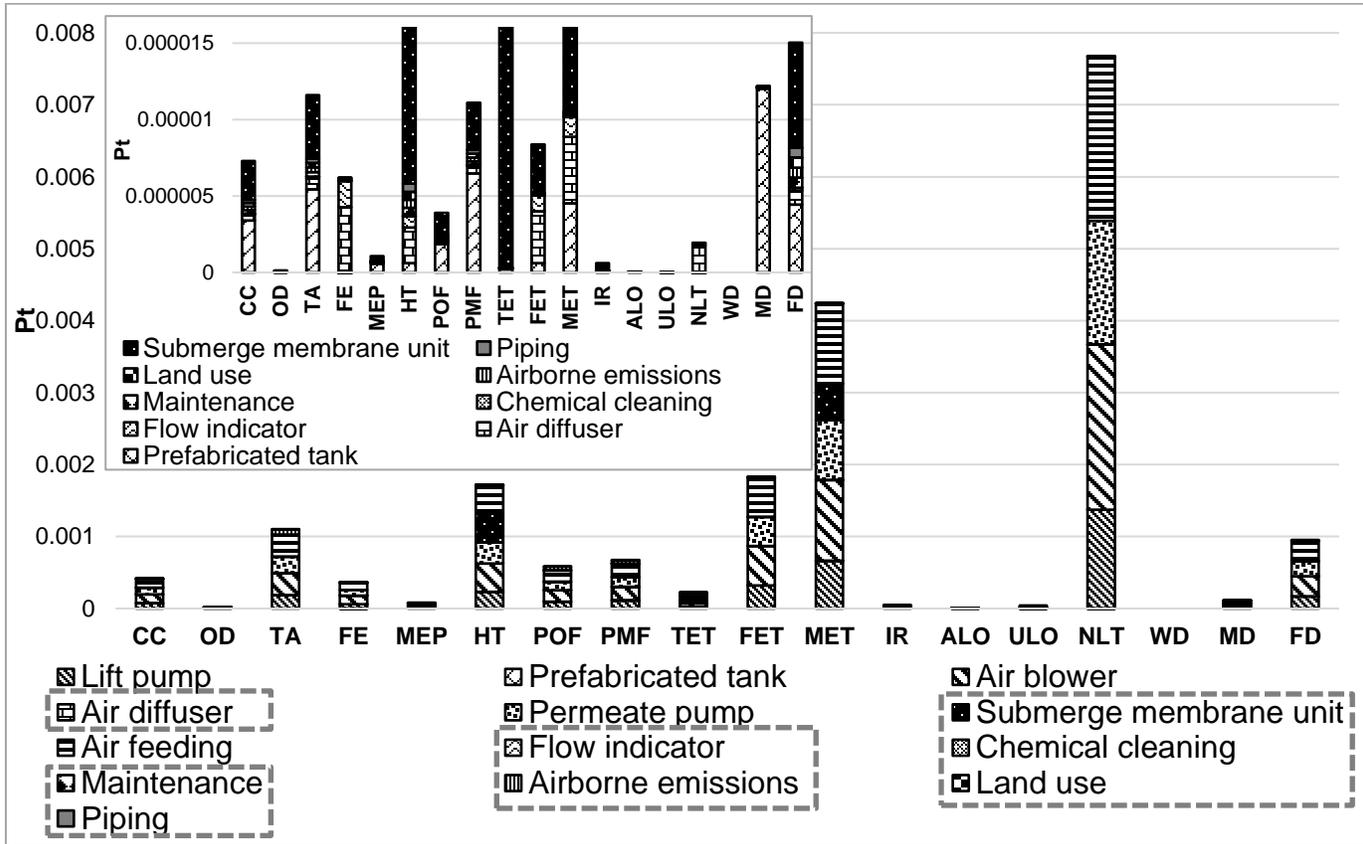
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Figure 2

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Figure 3

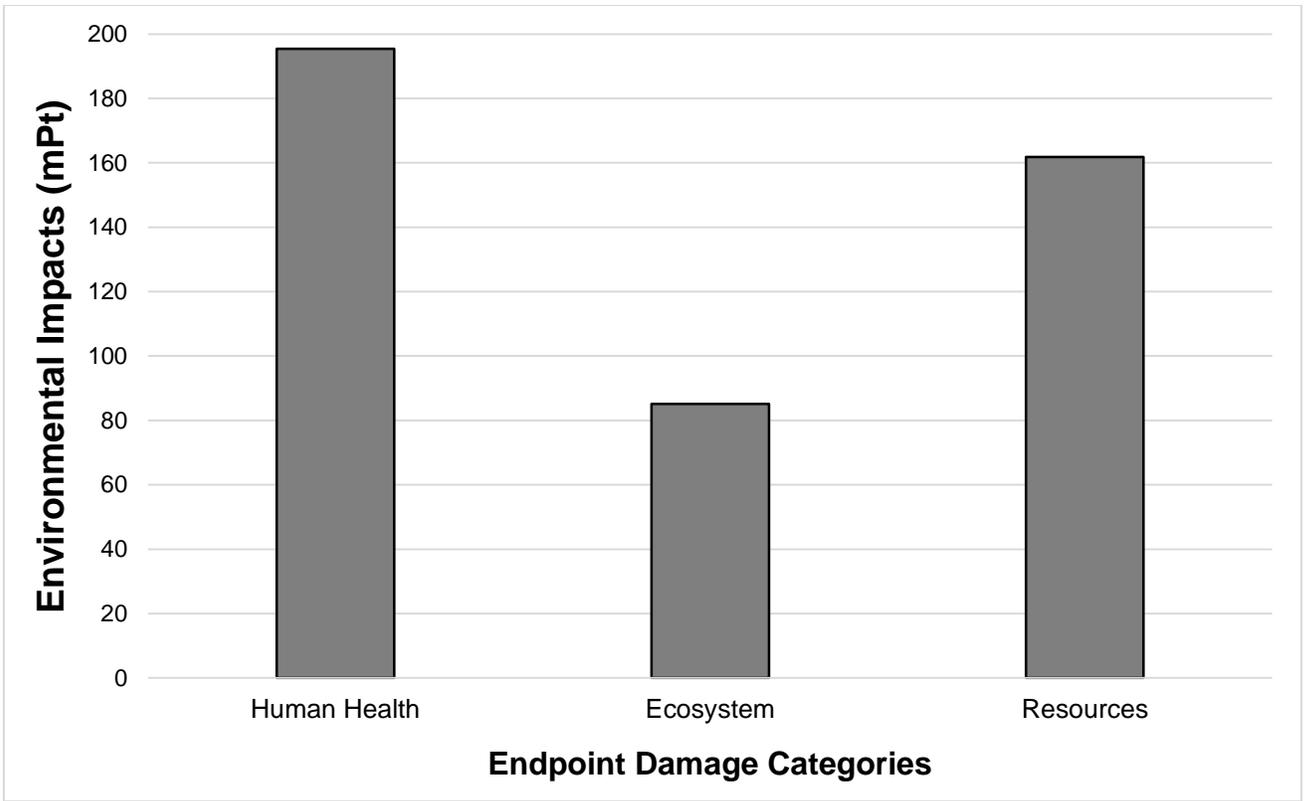


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Figure 4

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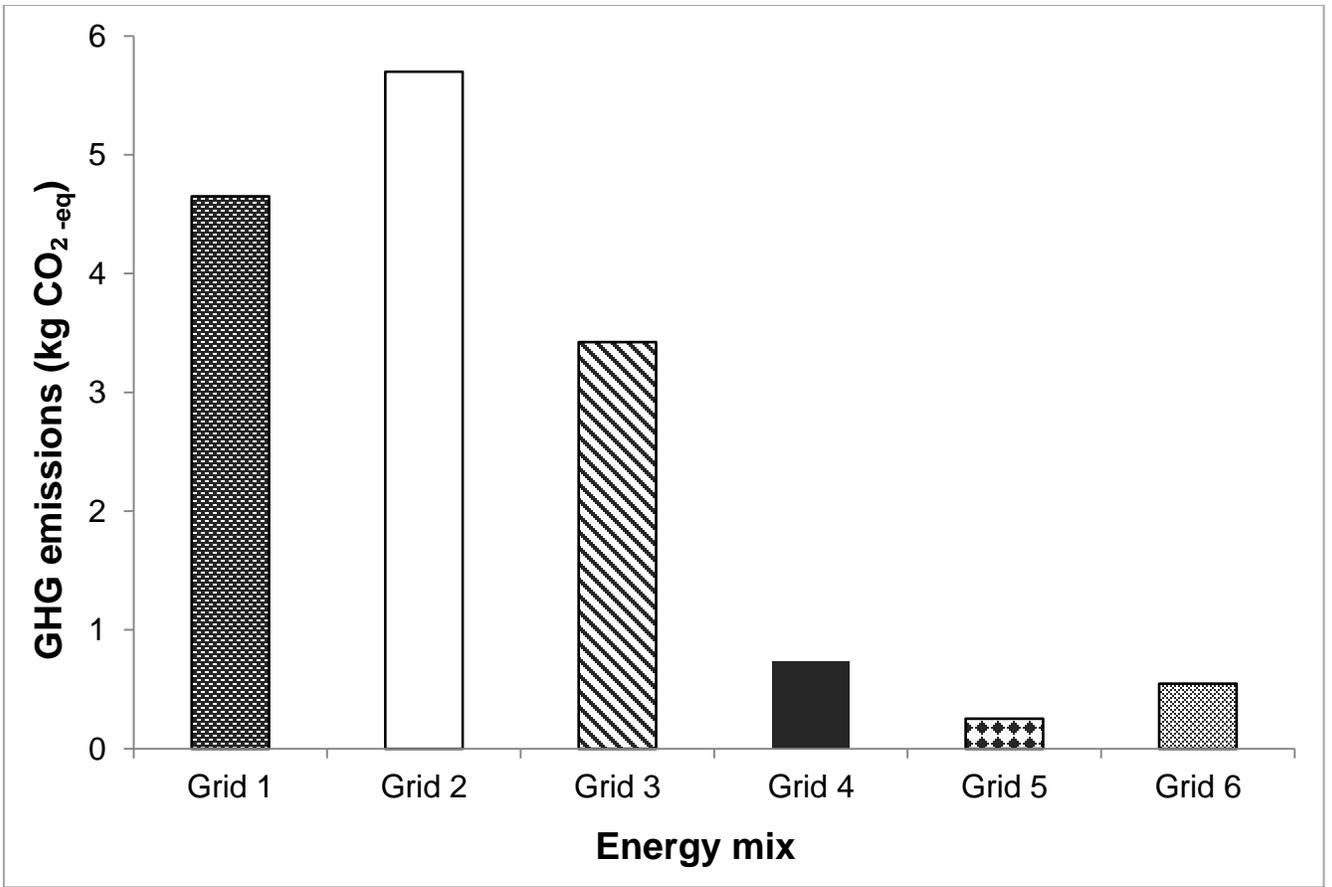


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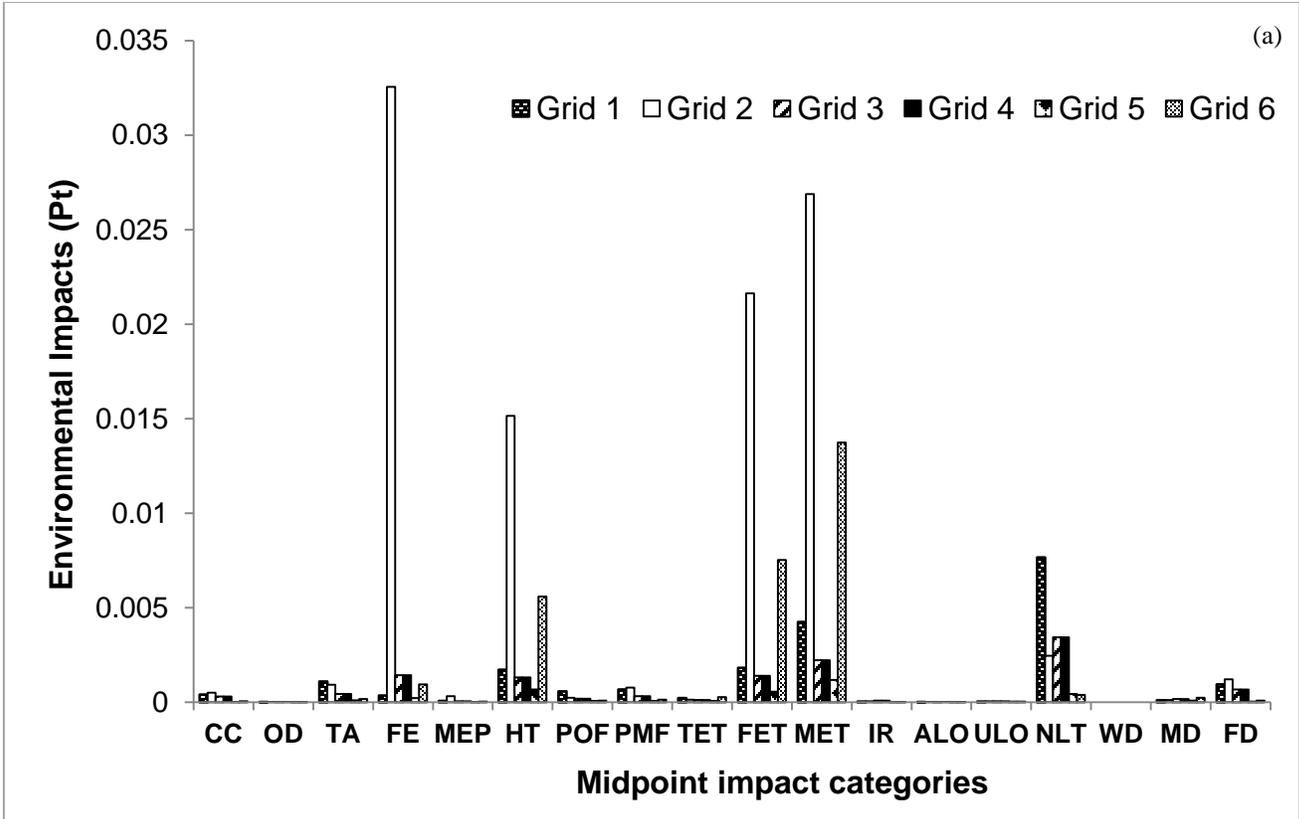
Figure 5



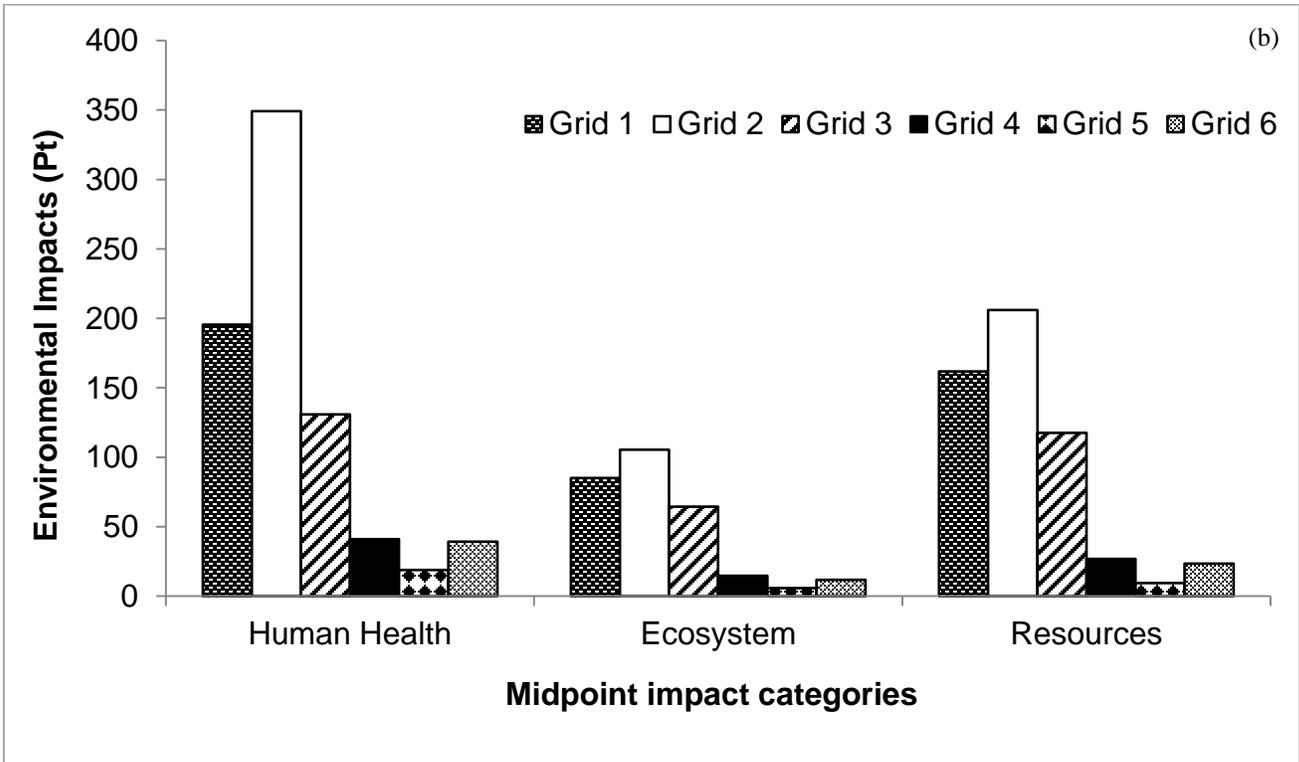
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Figure 6



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Figure 7